MODELING RECYCLED AGGREGATE CONCRETE CRACK
BY EXTENDED FINITE ELEMENT METHOD
AND CONCRETE DAMAGE PLASITICITY

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ABSTRACT

Crushing concrete to bring the aggregates back to be used for concrete structures is a process of creating recycled aggregate (RA). Recycled aggregate concrete (RAC) has become increasingly important in the field of construction. The use of recycled aggregate concrete made from recycled aggregate in civil engineering construction projects such as highways will provide both economic and environmental benefits in the near future. Achieving environmental sustainability will enable the earth's construction materials to support our future generations. Unfortunately, massive usage of RAC in the USA is not satisfying, even through the aging transportation infrastructure will inevitably produce tremendous amounts of waste concrete.

Concrete structures or pavements generally suffer from the crack problem. The morphology and growth process of cracks, most importantly, how these factors affect the concrete structure, is of great significance. The study of RAC is thus considerably needed to encourage the application of RAC. Crack modeling may lead to improved recycled aggregate concrete.

In this work, extended finite element approach and concrete damage plasticity material models are employed to predict the failure of recycled aggregate concrete. The recycled aggregate concrete was modeled based on a realistic concrete model with randomly distributed recycled aggregates. The arbitrary shapes of aggregates, and the new and old interfacial transition zones are constructed by using Fourier series. Recycled aggregate concrete models with or without initial crack are investigated. Results of using an extended finite element with both linear elastic fracture mechanics and cohesive segment approaches are discussed as well.

DEDICATION

This is dedicated to my loving parents, Zhiqiang Yang and Jun Wei, who always support, encourage, and push me to endeavor. Their love and understanding have encouraged me to continue working towards my goal. I also dedicate this paper to my friends, brothers and sisters in the church who helped me during the thesis period.

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CDP, Concrete damage plasticity

EFG, Element-free Galerkin

FE, Finite element

FEM, Finite element method

ITZ, Interfacial transition zone

LEFM, Linear elastic fracture mechanics

MLS, Moving-least-square

RA, Recycled Aggregates

RAC, Recycled aggregate concrete

Ref, Reference regular concrete

PCC, Portland cement concrete

RVE, Representative volume element

VCCT, Virtual crack closure technique

XFEM, Extended finite element method

CHAPTER 1

INTRODUCTION

The term “recycle” has gradually become one of the most important words around the world in recent decades. In the construction industry, recycling and saving resources are considered as key issues for sustainable future, which attract great attention.

In the field of civil engineering, recycled aggregates (RA) have promising potential for a variety of applications such as highway construction. There are various types of architectural structures, highway bridges, and infrastructures across the United States, which are in urgent need of major repairs, replacement or end of their design lifetime. The booming season of construction is around the comer, however, there are still a number of problems to be tackled, such as, the budget or availability of funds, and the environmental regulations.

The first recycled aggregate concrete (RAC) project can be traced back to the end of World War II (Olorunsogo & Padayachee, 2002). Aggregates from the ruins of the demolished concrete pavement have been widely applied as a stabilized base of some highway construction projects; this technique was successfully applied in the United States but also many other European countries.

Environmental protection has always been the hot topic in the past decades. Aggregates are the natural resources playing important role in the construction projects and reducing the usage of natural non-renewable resources during the construction is one of the most significant issues to be solved for human societies. Using recycle aggregates possesses several advantages:

- Reduce the raw materials consumption whilst maintain the available resources.
- Decrease energy cost during the production and transportation of aggregates.
- Decrease the amount of concrete waste generated from old buildings and structures.

1.1 Motivation

Aggregates have been extensively applied in a variety of materials in the field of construction industry; however they are not renewable natural resources which mean not environmental friendly. On the basis of the research revealed by FHWA in 2004 (Moo-Young, 2004), the recycled aggregates in Tennessee are at the undesirable situation. From their research, in 2004 Tennessee did not recycle concretes as aggregates, or as any aggregate base, not to mention reuse the concretes into new Portland cement concrete (PCC). So far, there are 41 states which have recycled concrete as aggregates, among them, 38 states out of 41 have been using the concretes as aggregate base, and 11 of them have already been using the recycled concrete aggregates in to the new PCC materials. These results indicate that Tennessee falls behind the most states in the United States towards the recycling of aggregates for sustainable future. Therefore, it is of great significance to investigate the current situation of recycled aggregates in Tennessee with the expectation of exploring a novel methodology to develop. To efficiently recycle the used concretes which manage to fabricate into renewable materials for the consideration of sustainability.

1.2 Literature Review

In the past two decades, there have been a lot of studies focused on the evaluation of the recycled aggregate (RA), interfacial transition zone (ITZ), and recycled aggregate concrete (RAC) performance and characteristics. The results leading to professionals suggest RCA forth putting in the real life field.

This section provides information through a general review of the different literatures from the United States and all over the world, with the same purpose of researches based on the RAC, which include the new ITZ, concrete mortar, RA, old ITZ, concrete damage plasticity (CDP) model, extended finite element method (XFEM) model, and virtual crack closure technique (VCCT) model.

Wells and Sluys (G. N. Wells, 2001) developed a novel methodology towards cohesive cracks model by using finite element. They used a non-linear model which includes interpolation part of displacement field and discontinuous displacement field. This model is utilized for the simulation of concrete fracture. They split the displacement field into two parts, which are continuous and discontinuous. The discontinuous part was utilized to complete independent of the mesh structure. It is different from the so-called ‘embedded discontinuity’ models, which are based on incompatible strain modes. There is no limit to use the displacement jumps element on the continuous across boundaries on the underlying type solid finite element model. Meshless methods mean the partition of unity function using for interpolate part of displacement field. By using shape function from a partition of unity:

$$\sum_{I \in N} N_I(x) = 1 \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (1.1)$$

Where:

N_I= Basis function (finite element shape function), related with a node I

$$u(x) = \sum_{I=1}^{n} N_I^k(x)(a_I + \sum_{J=1}^{m} b_{IJ}\gamma_J(x)) \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (1.2)$$

Where:

N_I^k = Partition of unity function of order k

a_J = Regular nodal degrees of freedom

b_{IJ} = Enhanced nodal degrees of freedom

γ_J = Enhanced basis with m terms

It is by using Equation (1.2) to connect meshless methods and FEM.

Six-noded triangle as general element was applied to implement the numerical process. The results of their study are this cohesive crack model method can be achieved by any general element; and the displacement jumps across element boundaries continuously and interpolation jump polynomial can be any sequence.

The work of Sukumar and Prevost (N. Sukumar, 2003) based on XFEM to model a quasi-static crack growth by the finite element program Dynaflow™ . Using of the isotropic linear elastic crack modeling, two-dimensional discrete functions and asymptotic crack tip displacement field could explain the factors which caused the crack. This makes no explicit domain through finite element modeling of the engagement surface cracks; therefore, quasi-static crack growth simulations cannot be remeshed. They study the 2-D cracks modeling embodiment described isotropic material and dual media. In particular, for the enrichment freedom array allocation, based on enrichment and mesh geometry query for execution of the node, and for the mounting procedure discrete equations were presented.

The typical failure modes of concrete can be categorized as crack in tension and crushing in compression. The study of Grassl, et al. (Peter Grassl, 2006) revealed the damage plastic model for concrete failure, in which two models were used as a combination of plasticity and damage model and damage plastic model.

They split the combination of plasticity and damage model into two sections, which combines plasticity base on the effective stress; and comprises combinations of plasticity based on the nominal stress.

First of all, two types of model combining plasticity and scalar damage were investigated. The correlations between stress and strain for this model is

$$\sigma = (1-\omega)\varrho = (1-\omega)D_e : (\varepsilon - \varepsilon_p) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1.3)$$

Where:

ω = A scalar describing the amount of isotropic damage

D_e = Elastic stiffness

ε = Total strain

ε_p = Plastic strain

ϱ = Effective stress

σ = Nominal stress

Then a study was carried out focusing on damage-plastic model for concrete failure. The yield function, the flow rule and the evolution law describe the plasticity part listed below.

$$f_y(\varrho, h_v) = \tilde{\varrho}(\varrho) - \sigma_y(h_v) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1.4)$$

Where:

f_y = Yield function

h_v = Plastic hardening variable

σ_y = Yield stress

$\tilde{\varrho}$ = Equivalent stress

For the damage plastic model, it includes the yield condition, hardening law, flow rule and the evolution law.

Hardening law

$$q_h(F_h) = \begin{cases} q_{h0} + (1 - q_{h0})F_h(F_h^2 - 3F_h + 3) & if\ F_h < 1 \\ 1 & if\ F_h \geq 1 \end{cases} \dots\dots\dots\dots\dots\dots\dots\dots (1.5)$$

Where:

q_h = Dimensionless variable

F_h = Hardening variable (the initial at $F_h = 0$, and the peak at $F_h = 1$)

The flow rule

$$\varepsilon_p = \lambda \frac{\partial P_p}{\partial \varrho}(\varrho, h_v) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (1.6)$$

Where:

λ = Plastic multiplier

P_p = Plastic potential

The evolution law

$$\theta = e_d(K_d) = 1 - \exp(-\frac{K_d}{\varepsilon_s}) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (1.7)$$

Where:

e_d = Evolution law

θ = Damage variable

$\mathrm{K_d}$ = Internal variable

ε_s = Parameter which control slope of softening curve

Hence, it can be concluded from their research that effective stress on plastic part is always appropriate for damage-plastic models. Moreover, the combination of plasticity and damage study provides suitable prediction towards the failure pattern of concrete. Last but not least, the damage plastic model can partially capture the reduction of shear stiffness on the basis of previous compressive loading.

Abdelaziz, et al. (Abdelaziz & Hamouine, 2008) presents an overview of the XFEM analysis in the latest developments on crack growth modeling. They list and summarize some important milestones of XFEM works. The XFEM is different from the classical finite element method (FEM), the requirement of no discontinuity is consistent with the border and for crack growth modeling does not need remeshing. Therefore it is possible to solve the engineering problems in complex domains, which may be practically impossible using classical FEM to solve. And XFEM has a great potential computational fracture tool. And XFEM can apply for more engineering problems than FEM.

Dong, et al. (Y. Dong, 2010) analyzed concrete fracture by applying cohesive crack method. In their study, the major element of the method is the element-free Galerkin method (EFG), which basically could model any crack propagation. The EFG is based on moving-least-square (MLS), which is a meshless discrete crack method.

$$u^{cont}(x) = \sum_{i=1}^{N} p_i(x) a_i(x) \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \text{(1.8)}$$

Where:

$p_i(x)$ = Polynomial basis, p is set to $p^T(x) = (1, x, y)$ hence N=3

$a_i(x)$ = Unknown coefficient

After comparing three different methods including FEM, EFG and crack segment method, it can be inferred that the advantage of the discrete crack method is the simplicity which then can be applied to many other crack situations. They have highly accurate simulation results from the usage of this discrete crack method.

In 2013, the study of Zhang, et al. (Zhang, Cao, Cao, & Li, 2013) used Abaqus to simulate fracture behavior of three points bending beam with initial crack. In their study, they use cohesive zone model, and VCCT to predict three-point bending concrete beam with initial crack in three-dimensional crack propagation.

$$u = \sum_{i=1}^{N} N_i(x)[u_i + H(x)\alpha_i + \sum_{a=1}^{4} F_a(x)b_i^a] \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots (1.9)$$

Where:

u = Displacement vector

N_i = Shape functions

u_i = Nodal displacement vectors

$H(x)$ = Jump function

α_i = Nodal enriched degree of freedom vector

F_a = Asymptotic crack-tip functions

b_i^a = Nodal enriched degree of freedom vector

In the XFEM displacement function Equation (1.9), asymptotic function and jump function are utilized with the purpose of the fracture analyses. In the XFEM method, there are three strain criterions and three stress criterions, which will be mentioned in the XFEM section. In the study of

XFEM, the maximum principal stress criterion is used as the evaluation factor of the material properties. For the VCCT method, it is based on the quantity of strain energy released when the crack is extended.

The results show the different methods that can be used to simulate different fracture toughness of the material as well as the type of fracture. The results indicate that: 1. XFEM can simulate any crack degree path for three-point bending concrete beam. 2. The combination of the numerical simulation and computational simulation technology can provide some basic realities of concrete beams capacity, and further assist for the design of concrete structures. 3. VCCT method is considerably appropriate for brittle materials, and also it can be applied to predict the softness process of concrete.

Roth, et al. (Simon-Nicolas Roth, 2013) presented a non-linear fracture mechanics approach for concrete crack propagation, which took advantage of XFEM crack model on damage mechanics. However, non-linear fracture mechanics (NLFM) approach was further applied in their study due to the massive limitation of the LEFM model. Furthermore, continuum damage model has been used based on its remarkable feature, which is capable of precise prediction and effective adjustment concerning the directions for crack in the process of crack propagation.(Simon-Nicolas Roth, 2013). A local crack-tracking technique is then developed to propagate a crack pattern along a single row of finite elements as a function of the equivalent principal stress direction. Using continuous damage mechanics calculating a predicted crack patch, and the predicted patch is proved to be correct. Once an inside element reaches a certain level of damage, the previous calculated level-sets will be used to apply the XFEM formulation with Heaviside function within this element introducing a discontinuity in the displacement field. Heaviside function to represent as a crack

$$H(z) = \begin{cases} 1, & z > 0 \\ 0, & else \end{cases} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1.10)$$

Used for approximate the function $\psi\ (x)$, the displacement approximation function becomes

$$u^d(x) = \sum_{\forall I} N_I(x)u_I + \sum_{\forall I} \varphi_I(x)\psi(x)\alpha_I = [H(f(x)) - H\left(f(x_J)\right)]\alpha_J \ldots\ldots\ldots\ldots\ldots\ldots (1.11)$$

Where:

N_I = Standard shape function of finite element method

u_I = Standard degrees of freedom

α_I = Additional degrees of freedom

Similar results from the local crack predicted and the real life experience were eventually obtained. The cracks start to grow and develop along the finite element and minimum damage level. Therefore the direction of the crack can be corrected because of the model utilized in the study.

The research by Pouya, et al.(Pouya & Bemani Yazdi, 2015) focused on the most fundamental ingredient of concrete, which is aggregate. In their study, damage-plasticity model was applied to experimentally run on crack failure of concrete. Moreover, they use elastic-plastic model to study the deformation and damage process in rock joints and interfaces in quasi-brittle geomaterials. They also separate displacement **u** to elastic part and plastic part; more importantly, develop the elastic damage model based on the elastic displacement part by the extent of the elastic stiffness. As for the plastic part, they have to deal with plastic yield, damage criterion, plastic potential, damage evolution and plastic hardening. The plastic potential is originate from the plastic displacement rate. The damage evolution **D** is correlated with cohesive cracks. From their research, the non-linear elastic-plastic models are used for the damage process and cohesive fractures. This model represents acurately the non-linear elastic behavior in the hardening and softening stages of material. This model was fitted to a variety of experimental results obtained on the basis of different geomaterials and a satisfying agreement between the model and experimental data was eventually obtained.

1.3 Recycled Aggregate

Recycled aggregates (RA) are mostly generated from crushed concrete and sometimes from asphalt, which can be used for many purposes. One of the major uses is for road base, such process saves money during the process of production and transportation. Furthermore, the utilization of RA protects the environment, since aggregates are made from natural rocks, which are nonrenewable resources.

RA contains old hydrated cement paste that is old mortar, which is from the previously mixed concrete product, apart from the original aggregate. The old mortar thus affects the characteristics of aggregates such as increased porosity.

1.4 Abaqus

Abaqus is a powerful computer-aided engineering simulation software, which designed for model generation, data analysis, results evaluation, and visualizing the finite element analysis result. Finite element analysis can resolve both simple linear problems, and most nonlinear simulations as well. Abaqus contains a large number of geometric elements library, which can simulate various kinds of geometries. Moreover, Abaqus contains a variety of material models, which could be used to define the behaviors of those materials. Designed as a general-purposed simulation tool, Abaqus can be used to investigate more than just structural (stress/displacement) problems; it can simulate problems under the condition of diverse areas such as heat transfer, mass diffusion, thermal management of electrical components (coupled thermal-electrical analyses), acoustics, soil mechanics (coupled pore fluid-stress analyses), piezoelectric analysis, electromagnetic analysis, and fluid dynamics.

Abaqus offers a wide range of capabilities for simulation of linear and nonlinear applications. Problems with multiple components are modeled by associating the geometry defining each component with the appropriate material models and specifying component interactions. In a nonlinear analysis system, Abaqus automatically selects appropriate load increments and convergence tolerances and continually adjusts them during the analysis to ensure that an accurate solution is efficiently obtained.

1.5 Thesis Overview

This thesis is divided into five chapters. Chapter I presents an introduction, which includes objectives, and literature review that briefly describes previous research on the RA characteristics, RAC behaviors, and previews studies on the extended finite element method (XFEM) and concrete damage plasticity (CDP) on the concrete material. Chapter II introduces necessary background about the methodologies and concrete damage material model to be used in this study, i.e. XFEM and CDP. Chapter III includes computer models, which inputs into the Abaqus simulation. Chapter IV presents simulation results, and findings for different cases of the RAC models with various boundary and loading conditions. Finally in the session of summary, conclusions, and discussions of this study are given. In the end, the future study arising from this research is briefly described.

CHAPTER 2

METHODOLOGY

2.1 Overview

The main goal of this study is to model the crack initiation and propagation of recycled aggregate concrete by using XFEM and nonlinear concrete damage plasticity constitutive material model. Crack growth with different boundary conditions, loadings and geometry of initial crack, and various modeling approaches are investigated.

In this chapter, the essential background about XFEM with both cohesive segments approach, linear elastic fracture mechanics (LFEM) approach, virtual crack closure technique (VCCT) approach, and concrete damage plastic (CDP) material model for simulation of damage and crack are explained. Then the random shape RA model based on the theory is given.

2.2 XFEM

The extended finite element method (XFEM) was developed by Belytschko and Black (Belytschko, 1999). XFEM also known as partition of unity method (PUM), is a numerical method which extends the classical finite element method (FEM). XFEM is a standard finite element simulation framework for strong (displacement) and weak (strain) of discontinuity numerical methods, which enable a local enrichment of approximation spaces. This method complements the shortage of FEM on cracks and material interfaces. There are some remarkable advantages of XFEM: there is no need to track the crack path in FE mesh problem(Datta, 2013); the geometry of the discontinuities do not need to match the mesh(Simulia, 2013). XFEM is a built-in model in the Abaqus, it employs the partition of unity framework to model the mesh (Babuska & Melenk, 1995) and analysis of crack initiation and propagation. XFEM makes it possible to allow the presence of discontinuities such as cracks in an element by defining extra terms in traditional displacement function. In the XFEM, special function is the partition of unity, which allows the presence of discontinuities in an element by enriching degrees of freedom with special displacement functions (Equation 1.9). The method is useful for solving an approximate fraction of the computational non-smooth domain.

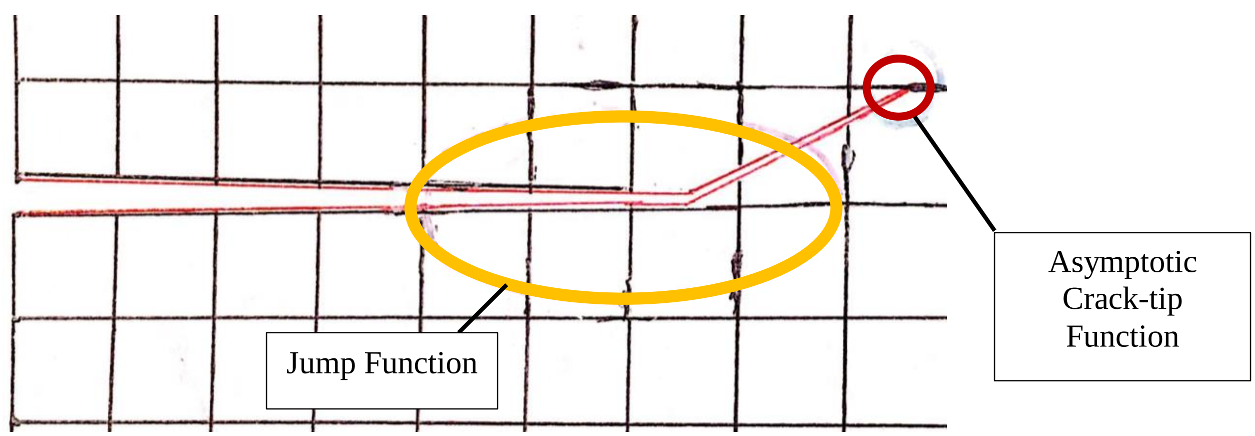


Figure 2.1 Functions applies on crack part (Du)

Shape function applies to all nodes in the model; Jump function applies to nodes, whose shape function support is cut by the crack interior; Asymptotic crack-tip function applies to node whose shape function support is cut by the crack tip (Figure 2.1). The jump function can be written as Equation 2.1, which is support cut by crack interior.

$$H(x) = \begin{cases} 1 & if\ (x - x_1) \cdot n \geq 0 \\ -1 & other\ wise \end{cases} \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \quad (2.1)$$

Where:

$x =$ Sample (Gauss) point

$x_1 =$ The closest point to x on the crack

$n =$ Unit outward normal to the crack at x_1

The tip function is given by

$$F_a(x) = \left[\sqrt{r} sin\frac{\theta}{2}, \sqrt{r} cos\frac{\theta}{2}, \sqrt{r} sin\theta \cdot sin\frac{\theta}{2}, \sqrt{r} sin\theta \cdot cos\frac{\theta}{2}\right] \cdots \cdots \cdots \cdots \cdots \cdots \quad (2.2)$$

Where:

$r, \theta =$ Polar coordinate system whit its origin at $\theta = 0$ and the crack tip (Simulia, 2013)

2.2.1 Traction-separation Cohesive Behavior

The traction-separation cohesive behavior approach is described in detail in "Modeling moving cracks with the cohesive segments method and phantom nodes" in "Modeling discontinuities as an enriched feature using the extended finite element method," (Simulia, 2013)

Cohesive segment approach uses traction-separation laws. And it follows the general framework for surface based cohesive behavior. This method can be used for brittle and ductile materials. The material properties define the evolution of damage leading to eventual failure. The material is to the section that is assigned to the crack domain.

In the traction-separation laws, the normal traction stress vector includes two or three components, which depends on dimensions.

We can choose to associate a normal behavior contact interaction property with the XFEM crack that defines the contact of cracked element surfaces. To assist the convergence as the material fails, localized damping can be introduced using the viscous regularization technique.

For the cohesive segments approach there are three stress based criteria and three strain based criteria, they are maximum principal stress (MAXPS), maximum principal strain (MAXPE), maximum nominal stress (MAXS), maximum nominal strain (MAXE), quadratic nominal stress (QUADS), and quadratic nominal strain (QUADE). Crack initiation bases on the stress/strain value at the center of enriched elements(Du).

Maximum nominal stress (MAXS) critical value

$$MAX\left\{\frac{[\sigma_n]}{N_{Max}} \quad \frac{\sigma_t}{T_{Max}} \quad \frac{\sigma_s}{S_{MAx}}\right\} = f, \quad [\sigma_n] = \begin{cases} \sigma_n \, for \, \sigma_n > 0 \\ 0 \, for \, \sigma_n < 0 \end{cases} \cdots\cdots\cdots\cdots\cdots\cdots (2.3)$$

Maximum nominal strain (MAXE) critical value

$$MAX\left\{\frac{[\varepsilon_n]}{\varepsilon_n^{max}} \quad \frac{\varepsilon_t}{\varepsilon_t^{max}} \quad \frac{\varepsilon_s}{\varepsilon_s^{max}}\right\} = f, \quad [\varepsilon_n] = \begin{cases} \varepsilon_n \, for \, \varepsilon_n > 0 \\ 0 \, for \, \varepsilon_n < 0 \end{cases} \cdots\cdots\cdots\cdots\cdots\cdots (2.4)$$

2.2.2 Linear Elastic Fracture Mechanics (LEFM)

The linear elastic fracture mechanics (LEFM) approach is one of the XFEM frameworks. It is designed for brittle crack propagation problems. It is similar to the XFEM cohesive method, however, it does not require asymptotic function and only the displacement jump function and shape function are considered. It is based on the modified Virtual Crack Closure Technique (VCCT) to calculate the strain energy release rate at the crack tip. The approach is more appropriate for brittle fracture problems and is described in detail in “Modeling moving cracks based on the principles of linear elastic fracture mechanics (LEFM) and phantom nodes” in “Modeling discontinuities as an enriched feature using the extended finite element method,” (Simulia, 2013). To use this approach, you must create a fracture criterion contact interaction property, as described in “Specifying fracture criterion properties for crack propagation” in “Defining a contact interaction property,” (Simulia, 2013).

2.2.3 Virtual Crack Closure Technique (VCCT)

The virtual crack closure technique (VCCT) is widely used for computing energy release rates based on results from continuum 2D and solid 3D finite element (FE) analyses to supply the mode separation required when using the mixed mode fracture criterion.

A variety of methods are used to compute the strain energy release rate based on results obtained from finite element analysis. The finite crack extension method requires two series of complete analyses. In the model the crack gets extended for a finite length prior to the second analysis. Based on the Griffith, this method provides one global total energy release rate, which is G, the crack propagation condition is.

$$G = G_c \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (2.5)$$

Where:

G = Fracture energy

G_c = Critical fracture energy

The total energy release rate is calculated by individual modes, which are modes I, II and III, are expressed in terms of the three stress intensity factors as follows (Bazant, 1992):

$$G_I = \frac{K_I^2}{E'}\ , G_I = \frac{K_{II}^2}{E'}, \text{and } G_I = \frac{K_{III}^2}{\mu} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.6)$$

Where:

μ = Shear modulus

E' = Young's modulus E (plane stress) or $E/(1-\nu^2)$ (plane strain).

And the total energy release rate is

$$G = G_I + G_{II} + G_{III} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.7)$$

The three critical energy release rates mentioned above are required in the Abaqus to specify as fracture criteria.

The method yields the total energy release rate as a function of the direction in which the crack was extended virtually, yielding information on the most likely growth direction. Modifications of the method have been suggested in the literature to allow the mode separation for two-dimensional analysis. An equivalent domain integral method that can be applied to both linear and nonlinear problems and additionally allows for mode separation was proposed in(Krueger, 2004). The methods above have been mentioned here briefly to complement the background information. A comprehensive overview of different methods used to compute energy release rates is given in(Krueger, 2004). Alternative approaches to compute the strain energy release rate based on results obtained from finite element analysis have also been published recently by Krueger(Krueger, 2004).

To study the onset and propagation of cracking in quasi-static problems using the virtual crack closure technique (VCCT), VCCT uses the principles of linear elastic fracture mechanics (LEFM), so it is appropriate for problems in which brittle crack propagation occurs along predefined surfaces. VCCT is based on the assumption that the strain energy released when a crack is extended by a certain amount is the same as the energy required closing the crack by the same amount(Simulia, 2013).

Virtual closure technique (VCCT) based on the energy release rate as interaction property. The VCCT criterion uses the principles of linear elastic fracture mechanics (LEFM). The LEFM is more appropriate for brittle fracture. Considering the concrete is a semi-brittle material; in this study XFEM LEFM was used based on VCCT to compare the results with other methods.

2.3 Concrete Damage Plasticity (CDP)

Concrete damage plasticity (CDP) is another concept, which builds on the basis of model in the Abaqus. This material model is compatible to various types of concrete structural modeling. The concept of combining an isotropic elastic damage, isotropic tensile and compressive plasticity indicates a specific combination of inelastic behavior (Simulia, 2013).

Damaged plasticity model can be used for concrete materials. Concrete stress-strain has different patterns in tension and in compression, as demonstrated in Figure 2.2. In the part of tension, linear elastic increases with the tension stiffening; and in compression, linear elastic firstly follows strain hardening, and then strain softening. Concrete will unload, during tension stiffening or strain softening stages; depending on Young's modulus E. There are two major variables, which are tensile damage variable d_t and compressive damage variable d_c (Hailing Yu, 2011).

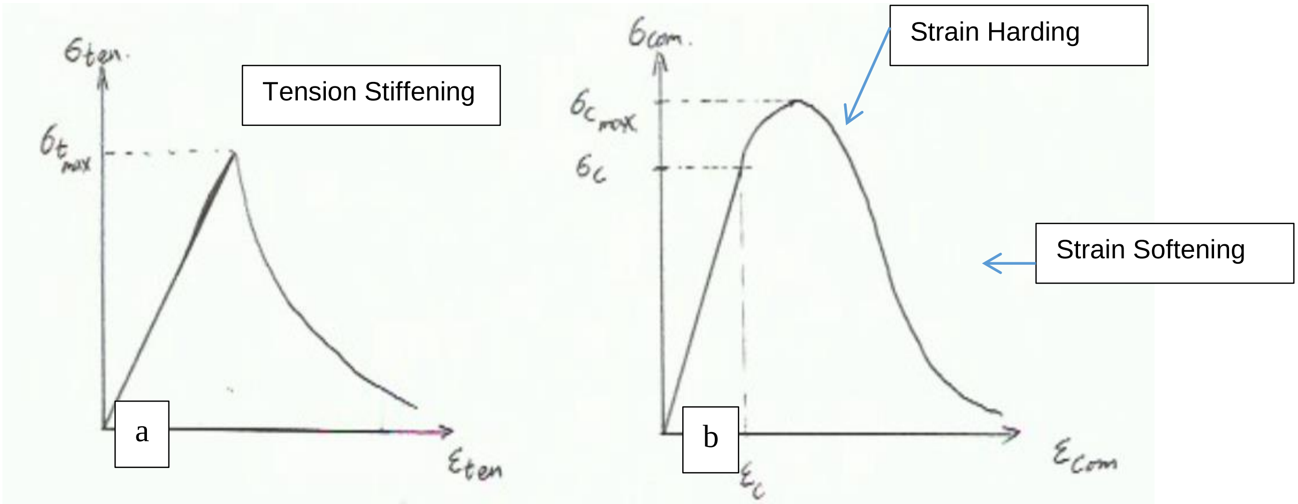


Figure 2.2 Concrete behaviors in (a) tension (b) compression

The Concrete Damaged Plasticity Model uses the concept of isotropic damaged elasticity in combination with isotropic tensile and compressive plasticity to represent the inelastic behavior of concrete. In contrast to the Brittle Cracking Model it allows the definition of strain hardening in compression and can be defined to be sensitive to the straining rate, which resembles the behavior of concrete more realistically. The Concrete Damaged Plasticity Model is designed for applications in which concrete is subject to cyclic loading with alternating tension compression loading. The model allows stiffness recovery during cyclic loading reversals. In contrast to the Brittle Cracking Model the Concrete Damaged Plasticity Model does not contain a failure criterion and thus does not allow the removal of elements during the analyses. This makes it rather difficult to model missile impact phenomena where perforations of the missile through the reinforced concrete slab are of most probability. On the other hand, the Concrete Damaged Plasticity Model may be used in conjunction with adaptive meshing. Adaptive meshing means that the impacted zone of the concrete slab is remeshed regularly during the analyses in order to avoid heavy distortion of the elements. This allows the completion of the analyses even to relatively high deformation rates (Simulia, 2013).

2.4 Random Shape Generation of Aggregate and ITZs

The shape of aggregates (Figure 2.3) can be represented by the Fourier series function (Al-Ostaz, Wu, Alkhateb, & Alzebdeh, 2009; Garboczi, 2002).

$$\mathrm{R}(\theta) = \alpha_0 + \sum_{n=1}^{\infty} (\alpha_n \cos(n\theta) + \beta_n \sin(n\theta)) \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots (2.8)$$

where the coefficients α_n and β_n are

$$\alpha_n = \frac{1}{2\pi} \int_0^{2\pi} R(\theta) \cos(n\theta)\, d\theta \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots (2.9)$$

$$\beta_n = \frac{1}{2\pi} \int_0^{2\pi} R(\theta) \sin(n\theta)\, d\theta \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots (2.10)$$

In practice the continuous integrals in equations 2.6 and 2.7 are estimated by:

$$\alpha_n = \frac{1}{N} \sum_{m=0}^{N-1} R(\theta_m)\cos(n\theta_m) \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots (2.11)$$

$$\beta_n = \frac{1}{N} \sum_{m=0}^{N-1} R(\theta_m)\sin(n\theta_m) \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots (2.12)$$

where N is the number of sample points. A Fourier series involving N terms of coefficients can precisely represent the discrete function sampled at N points. By the symmetry of the coefficients α_n and β_n equation 2.8 can be rewritten as

$$\mathrm{R}(\theta) = \alpha_0 + \sum_{n=1}^{N-1} \alpha_n \cos(n\theta) + \alpha_n \cos((N-n)\theta) + \beta_n \sin(n\theta) - \beta_n \sin((N-n)\theta)) \dots \dots \dots (2.13)$$

where N_t is the number of terms used in the series that approximate $R(\theta)$.

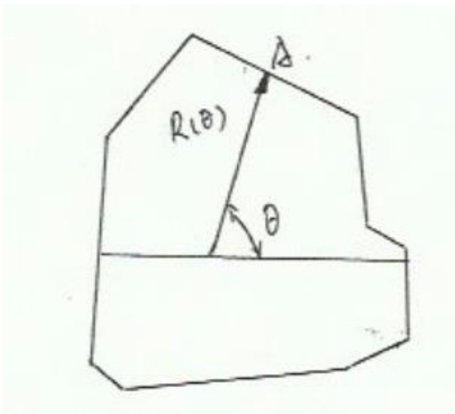


Figure 2.3 The aggregates shape.

A Matlab script based on the description above is used to generate irregular shapes of aggregates whose centroids are randomly distributed within the representative volume element (RVE) in a two dimensional RAC concrete model as shown in Figure 2.3.

CHAPTER 3

MATERIALS

3.1 2D RCA Models

When producing concrete with recycled aggregates, the irregular aggregates are surrounded first by a thin layer of old ITZ, next to old mortar, then enclosed by new ITZ and bulk new fresh mortar. The two-dimensional RCA concrete model is shown in Figures 3.1.

In this study, there are three RCA models. There are concrete model without notch (Figure 3.1), concrete model with two rectangular notches in the middle of the left and right side, notch size is $1mm \times 2mm (H \times W)$ (Figure 3.2), and the last model, which is two triangular notches in the middle of the left and right side, these notches have size $1mm \times 2mm$ $(b \times h)$ (Figure 3.3).

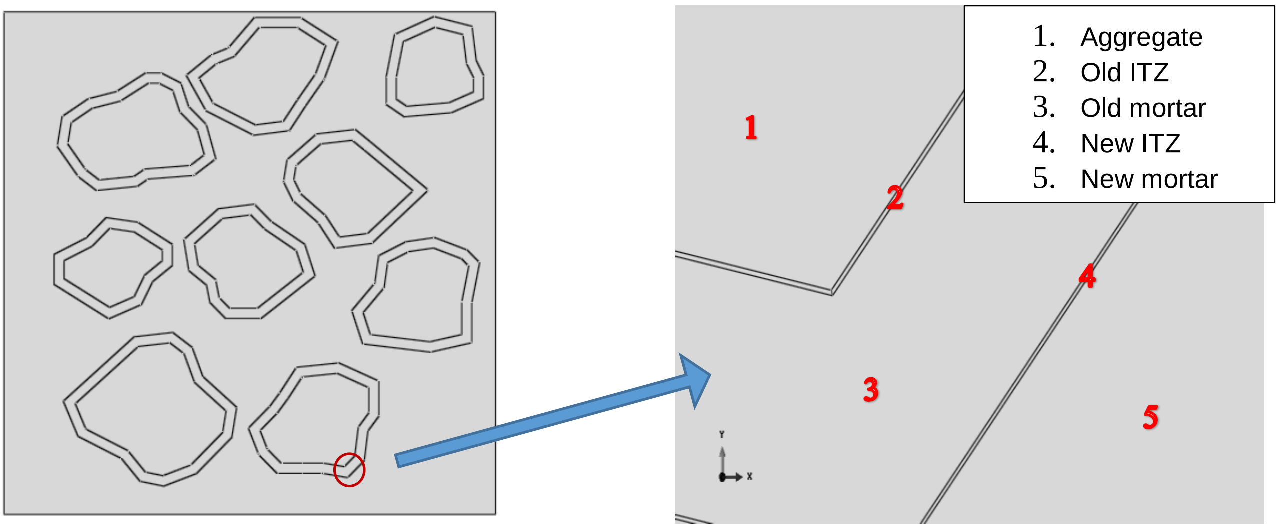


Figure 3.1 A $150mm \times 150mm$ 2D RAC model without notch

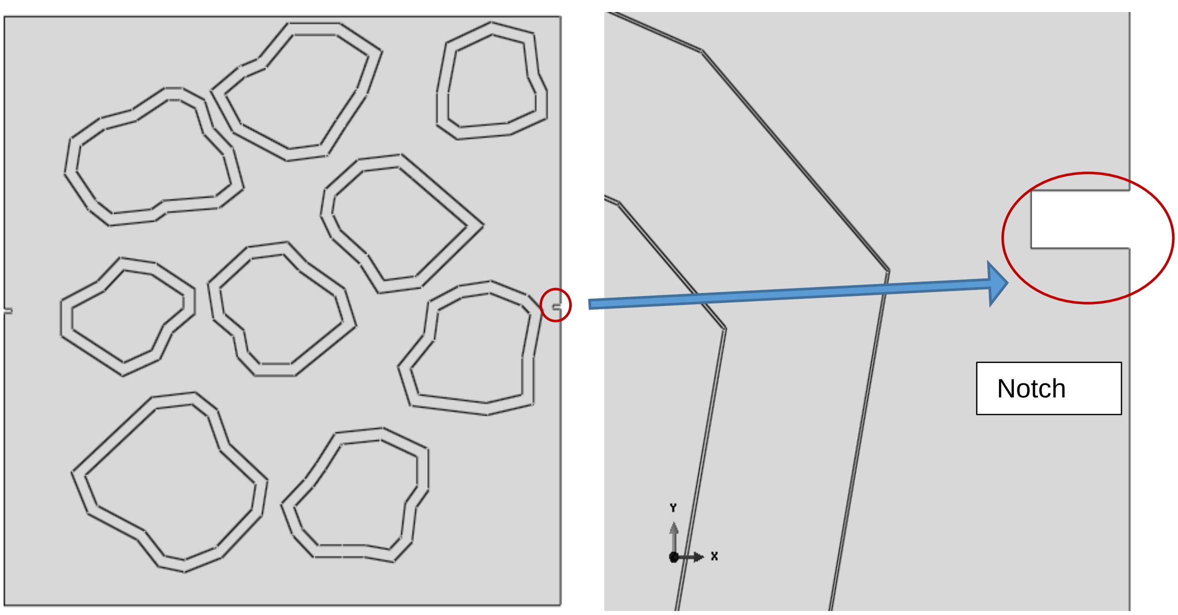


Figure 3.2 A $150mm \times 150mm$ 2D RAC model with notch

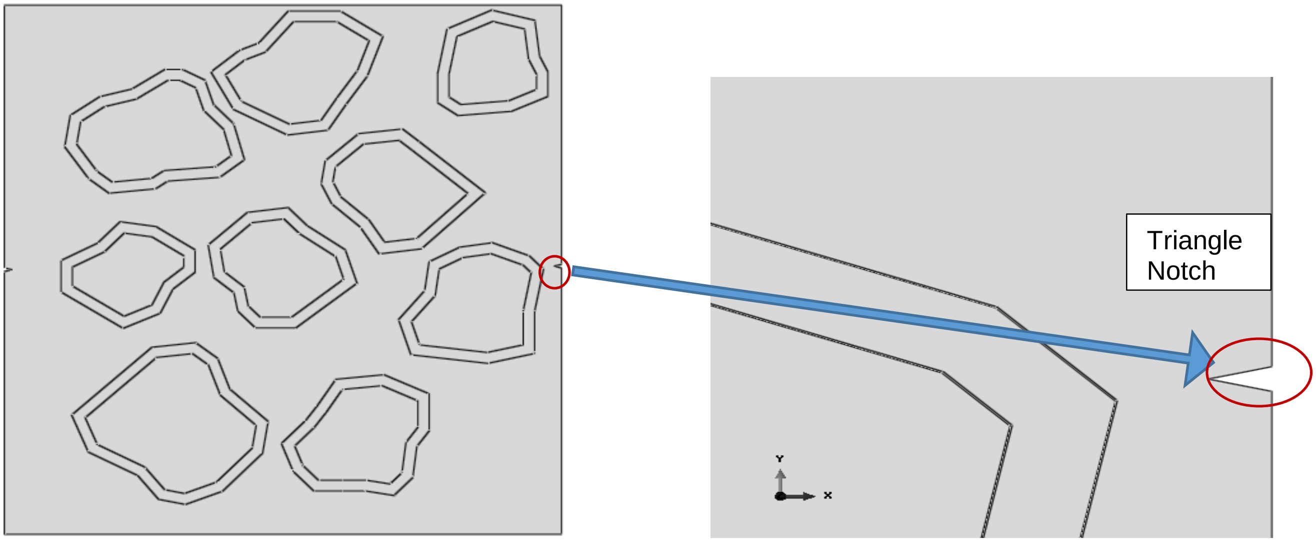


Figure 3.3 A $150mm \times 150mm$ 2D RAC model with triangle notch

3.2 Loads and Boundary Conditions

In this study, different boundary, loading conditions and various geometry of initial crack and multiple simulation approaches were applied to model the crack patterns, initiation and propagation in recycled aggregate concrete. The simulations are performed by using commercial FEM package Abaqus which is robust in nonlinear finite element modeling. Boundary conditions are shown in Figure 3.4.

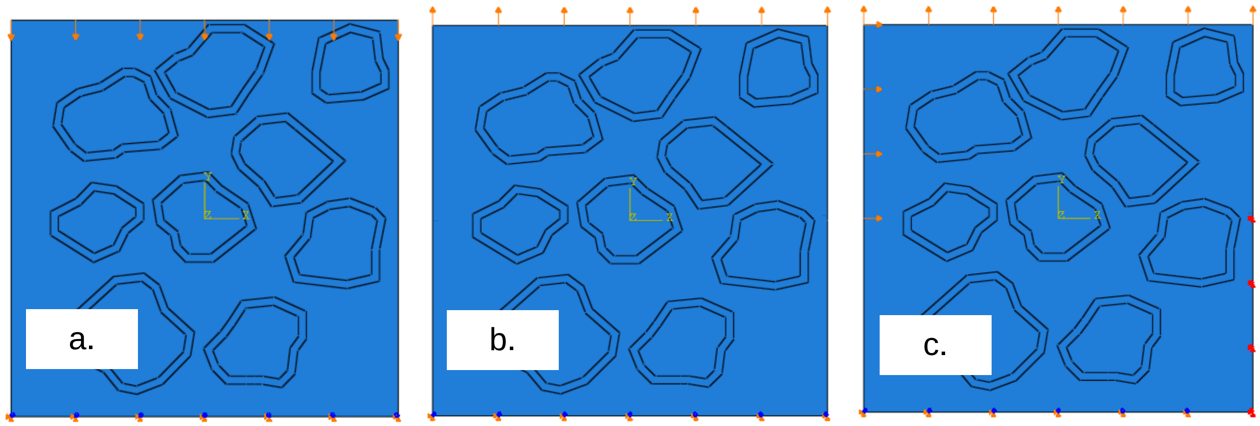


Figure 3.4 Models boundary conditions (a) compression (b) tension (c) tension-shear

3.2.1 CDP Loads and Boundary Conditions

Situation 1: The only uniaxial load is applied compression displacement load along on the vertical direction with -0.6mm on the top and the bottom is fixed end (Figure 3.4a).

Situation 2: The only uniaxial load is applied in tension, displacement along vertical direction of 0.03 mm is applied on the top. And the bottom is fixed end (Figure 3.4b).

Situation 3: Tension-shear is applied by a combination of displacement load along horizontal direction with a value of 0.06 mm on the top half of the left side, tensile load in displacement along vertical direction with 0.03 mm on the top, the bottom half of the right side and the bottom are fixed end. (Figure 3.4c)

Table 3.1 CDP Model Approach

Case	Concrete	BC	Bottom (u: mm)	Left (u: mm)	Top (u: mm)	Right (u: mm)
1	Ref.	Compression	0	-	-0.6	-
2	RAC	Compression	0	-	-0.6	-
3	RAC-Tri-Notch	Compression	0	-	-0.6	-
4	Ref	Tension	0	-	0.03	-
5	RAC	Tension	0	-	0.03	-
6	RAC-Notch	Tension	0	-	0.03	-
7	RAC-Notch	Tension-shear	0	0.06	0.03	0

3.2.2 XFEM Cohesive Loads and Boundary Conditions

Situation 1: The only uniaxial load is applied in tension, displacement along vertical direction of 0.03 mm is applied on the top and the bottom is fixed end. (Figure 3.4b)

Situation 2: Tension-shear is applied by a combination of displacement load along horizontal direction with a value of 0.02 mm on the top half of the left side, tensile load in displacement along vertical direction with 0.02 mm on the top, the bottom half of the right side and the bottom are fixed end. (Figure 3.4c)

Table 3.2 XFEM Model Cohesive Segment Approach

Case	Concrete	BC	Bottom (u: mm)	Left (u: mm)	Top (u: mm)	Right (u: mm)
8	Ref	Tension	0	-	0.03	-
9	RAC	Tension	0	-	0.03	-
10	Tri-Notch	Tension	0	-	0.03	-
12	RAC-Notch	Tension	0	-	0.03	-
13	RAC	Tension-shear	0	0.02	0.02	0
14	Tri-Notch	Tension-shear	0	0.02	0.02	0
15	RAC-Notch	Tension-shear	0	0.02	0.02	0

3.2.3 FEM VCCT Loads and Boundary Conditions

Situation 1: The only uniaxial load is applied in tension, displacement along vertical direction of 0.05 mm is applied on the top and the bottom is fixed end (Figure 3.4b).

Situation 2: Tension-shear is applied by a combination of displacement load along horizontal direction with a value of 0.06 mm on the top half of the left side, tensile load in displacement along vertical direction with 0.05 mm on the top, the bottom half of the right side and the bottom are fixed end (Figure 3.4c).

Table 3.3 FEM LEFM-based VCCT Approach

Case	Concrete	BC	Bottom (u: mm)	Left (u: mm)	Top (u: mm)	Right (u: mm)
16	RAC	Tension	0	-	0.05	-
17	RAC	Tension-shear	0	0.6	0.05	0

As the Abquas requires the energy criteria for VCCT approach, the criteria is provided in Table 3.4.

Table 3.4 VCCT Approach Fracture Criteria Properties

Critical energy release rate (N/mm)			Exponent am	Exponent an	Exponent ao
G_{If}	G_{IIf}	G_{IIIf}			
0.0333	0.0333	0.0333	1	1	1

The complete set of parameters to define the CDP constitutive model for old and new mortar, old and new ITZ is scarce in current literatures. The parameters are listed in the Table 3.5.

New and old ITZ damage plasticity properties are adopted from Zhang et al. (Zhang et al., 2013). Elastic properties adopted from Li et al.(Li, Xiao, & Corr, 2013); use CDP material data in Jankowiak and Lodygowski (Tomasz JANKOWIAK, 2005) Identification of parameters of concrete damage plasticity constitutive model to approximate material property of new and old mortar are dopted from Li et al 2013 (Li et al., 2013).

Table 3.5 Table Elastic and Plastic Parameters

Materials	Elastic Modulus (Mpa)	Poisson's ratio	Dilation angle	Eccentricity	fb0/fc0	K
Aggregate	20200	0.27	15	0.1	1.16	0.66
New ITZ	18000	0.2	38	0.1	1.12	0.667
New Mortar	23000	0.22	38	0.1	1.12	0.667
Old ITZ	20000	0.2	38	0.1	1.12	0.667
Old Mortar	25000	0.22	38	0.1	1.12	0.667

Through the different studies, it is revealed that old ITZ and new ITZ thickness was estimated by locating the places where there is slight variation in the indentation modulus with the distance from the natural aggregate or old mortar matrix surface, and the indentation modulus distribution of the ITZs seem to be close to those of corresponding old mortar matrix and new mortar matrix. Based on the nanoindentation results, the thicknesses of old ITZ and new ITZ are found to be around 50 μm and 60 μm, respectively (Li et al., 2013). They defined the old ITZ and new ITZ Poisson's ratios as 0.20. Experimental data are listed in the Table 3.6,

Table 3.6 Material Properties of Each Phase in RAC (Li et al., 2013)

RAC	Thickness (μm)	Elastic Modulus (MPa)	Poisson's Ratio (ν)	Strength (MPa)	
				Compressive	Tensile
Old ITZ (OI)	50	20	0.2	36	2.4
New ITZ (NI)	60	18	0.2	33.1	2.21

CHAPTER 4

RESULTS

The crack patterns using CDP constitutive material model, crack initiation and propagation by applying XFEM simulation techniques are presented in this chapter.

4.1 Results by Using CDP

This section will give the results by running CDP model in the different concrete models and boundary conditions.

4.1.1 Results by Using CDP under Compression

By using CDP model simulation specimens are rated by the concrete compression damage parameter d_c, where $0 \leq d_c \leq 1$. This parameter illustrates the potential of the concrete crack location. When the parameter is approaching to 1, red part as shown in Figure 4.1 and Figure 4.2, which means the point at that location is considerably easier for crack to develop. The parameter is close to 0 or equal to 0, blue part in the figure, indicating no crack going to take place in that area.

As seen in Figure 4.1, the damage parameter in ITZs is more critical compared to other areas. The potential creaks are initiated from ITZs around aggregates and formed in strips which are generally in 45 or 135 degrees. This is reasonable since ITZ in concrete is believed to be the most fragile part.

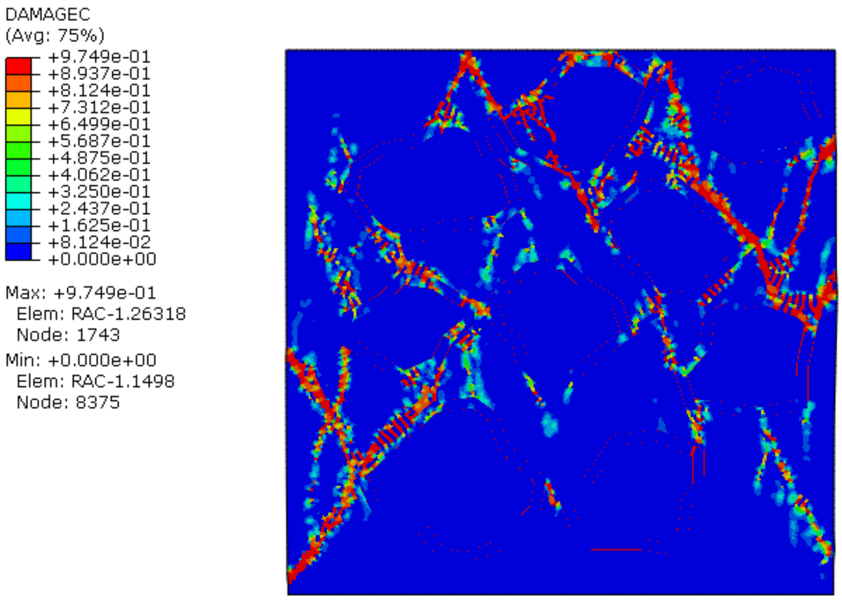


Figure 4.1 Damage indicator d_c contour plot of RAC by using CDP

Figure 4.2 shows the contour plot of referenced regular concrete under compression, the crack pattern in this case is very similar to the one for RAC. There seems more critical regions found in the reference concrete. The strips are slightly wider than those in RAC. Thus RAC may not be as susceptible to crack as regular concrete and crack resistance is improved by using RAC.

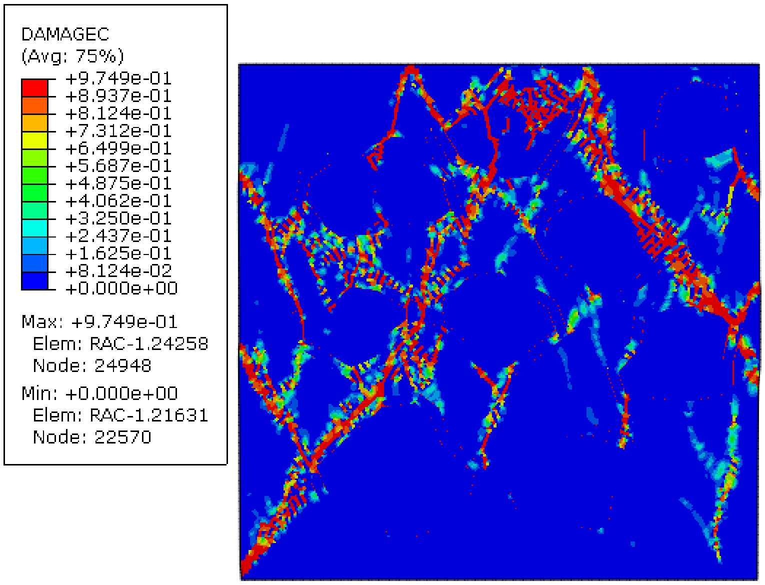


Figure 4.2 Damage indicator d_c contour plot of regular concrete by using CDP

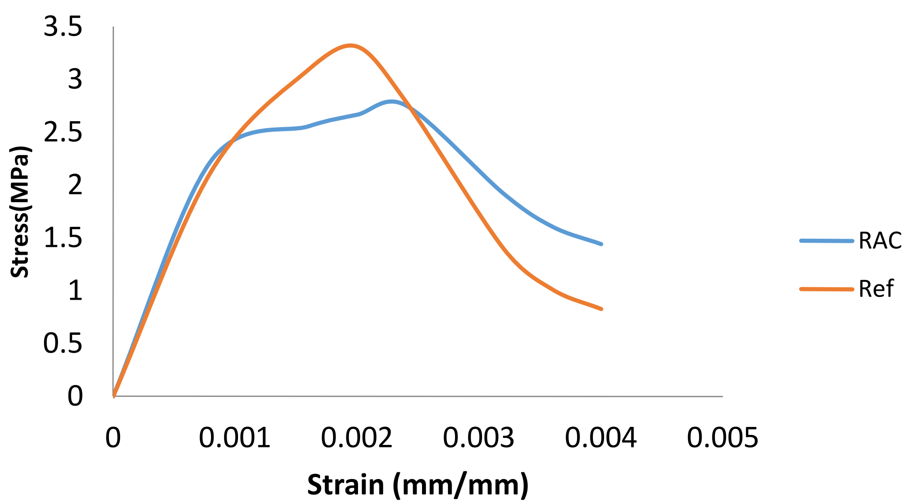


Figure 4.3 Comparison of stress-strain curves for RAC and reference regular concrete (Ref) under compression by CDP

Stress-strain response for recycled aggregate and reference regular concrete is shown in figure 4.3. At the linear elastic stage, RAC and Ref have almost the same stiffness (Modulus of elasticity). The peak stress of RAC is not as high as that of regular concrete while the stress level in the RAC is higher at the softening stage. RAC is expected to have larger failure strain.

4.1.2 Results by Using CDP under Tension

In the CDP model simulation specimens are rated by the concrete tension damage parameter d_t, where $0 \leq d_t \leq 1$. This parameter illustrates the potential of the concrete crack location. When the parameter is closing to 1, red part in the Figure 4.4 to Figure 4.6, which means at that location it is relatively easier for the crack occurs. And the parameter is closing to 0 or equal to 0, blue part shown in the figure, which means no crack going to be in that area.

The damage tension indicator d_t contour plot for RAC under tension is presented in Figure 4.4. One may easily observe that ITZs around aggregates in the top portion are critical regions. Crack may initiate from the side on the top part and propagate along the critical region of ITZ.

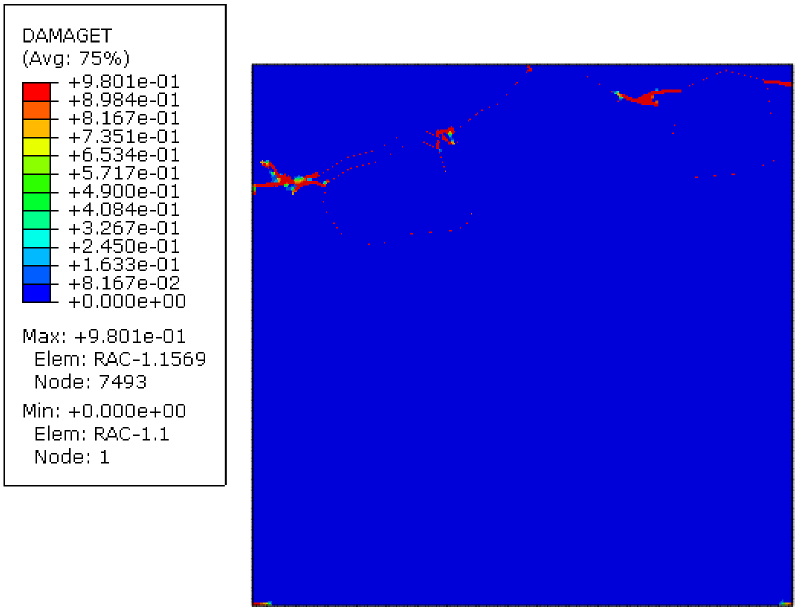


Figure 4.4 Damage indicator d_t contour plot of RAC by using CDP

The damage tension indicator d_t contour plot for reference regular concrete under tension is given in Figure 4.5. More and wider critical potential crack strips are seen and several potential crack strips are found to connect ITZs of two neighboring aggregates. More critical regions are found in the middle section in the model.

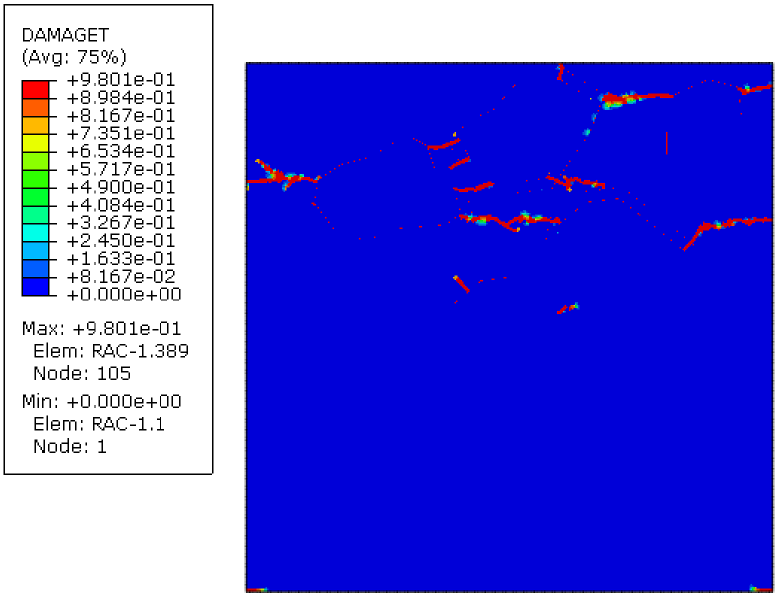


Figure 4.5 Damage indicator d_t contour plot of reference regular concrete by using CDP

Figure 4.6 is the contour plot of damage indicator d_t of RAC with rectangular notches when it is subjected to tension displacement. Obviously the cracks initiate from both notches. Potential crack regions are seen in those ITZs generally above the two notches.

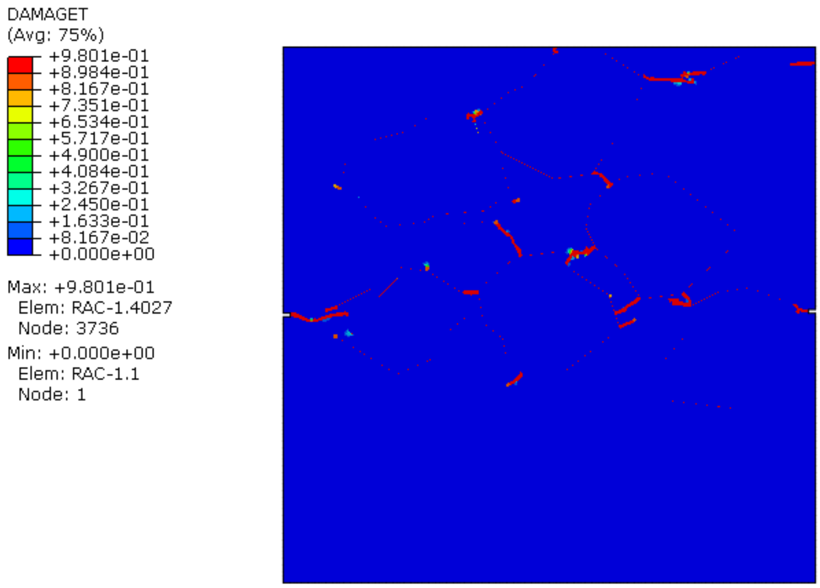


Figure 4.6 Damage indicator d_t contour plot of RAC with notch by using CDP

The stress-strain responses of RAC and reference regular concrete under tensile load is given in figure 4.7. At the linear elastic stage, the two curves almost coincide. Overall, there is very little difference of the stress-strain behavior between RAC and regular concrete.

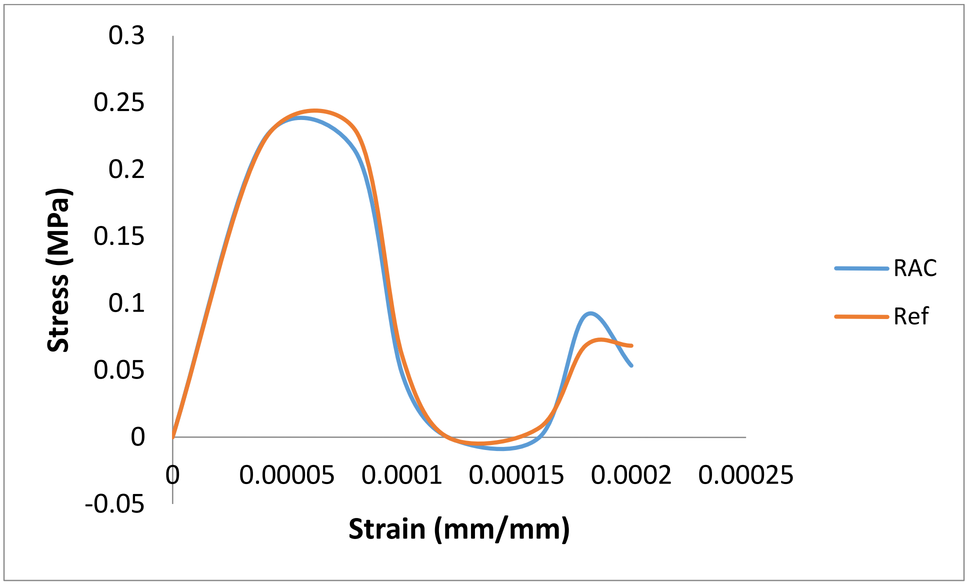


Figure 4.7 Comparison for stress-strain Curves for RAC and reference regular concrete (Ref) under tension by CDP

4.1.3 Results by Using CDP under Tension-shear

The stress contour of RAC under tension-shear is shown **in** Figure 4.8. One may easily see higher stress in the region between the two notches. Cracks are expected within that region.

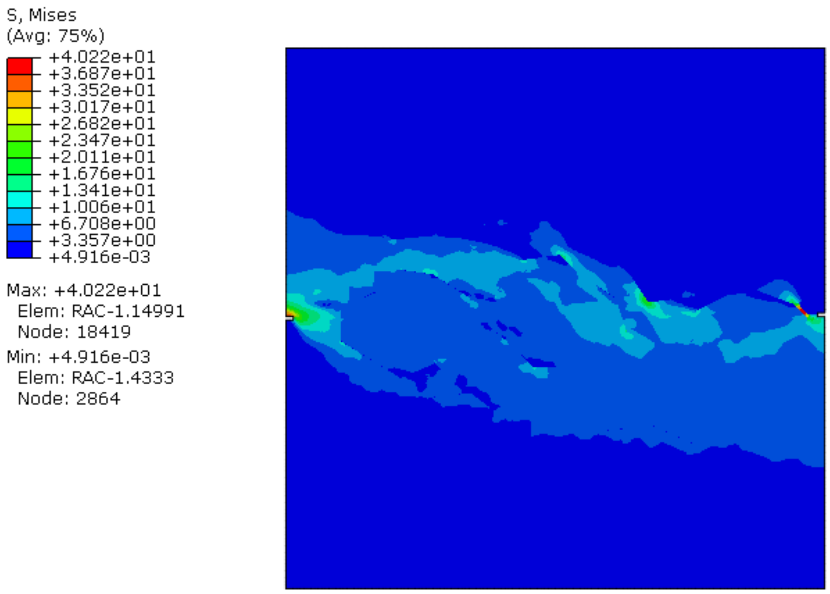


Figure 4.8 Stress contour of RAC with notches under tension-shear by CDP

4.2 Results by Using XFEM

This section gives the results of crack modeling obtained by XFEM using both Cohesive segment and LEFM-VCCT approaches with different boundary conditions. Potential cracks are visualized through plots of the signed distance function PHILSM.

4.2.1 Results by XFEM using cohesive segments approach under tension

The PHILSM results given by XFEM using cohesive segments approach under tensile load are presented in Figures 4.9 through 4.12. The results show notch shape dependency when modeling the crack of concrete. It seems that crack is more sensitive to the rectangular notch.

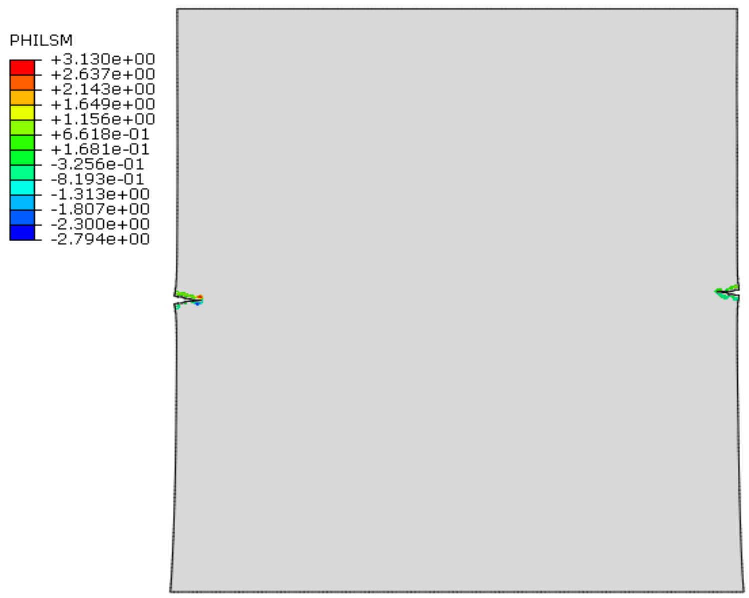


Figure 4.9 Signed distance function plot of references regular concrete under tension by XFEM using cohesive segment approach

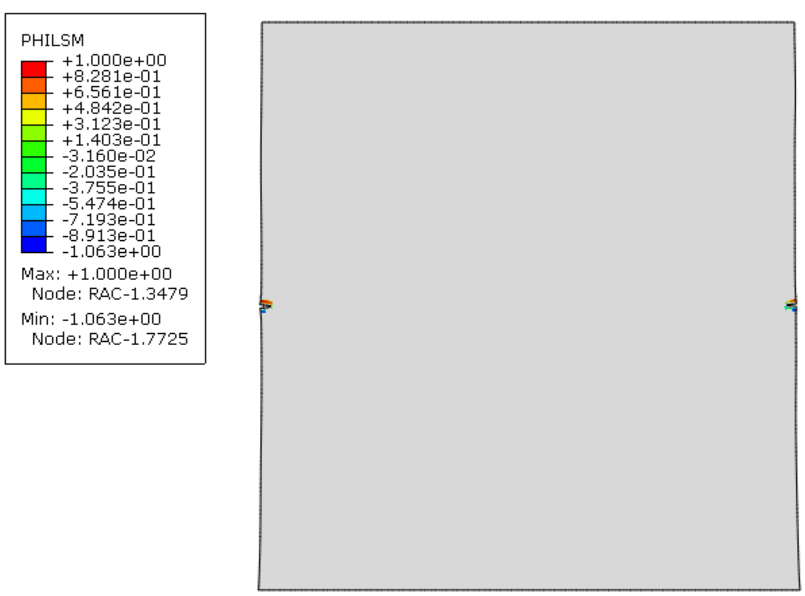


Figure 4.10 Signed distance function plot of RAC under tension by XFEM using cohesive segment approach

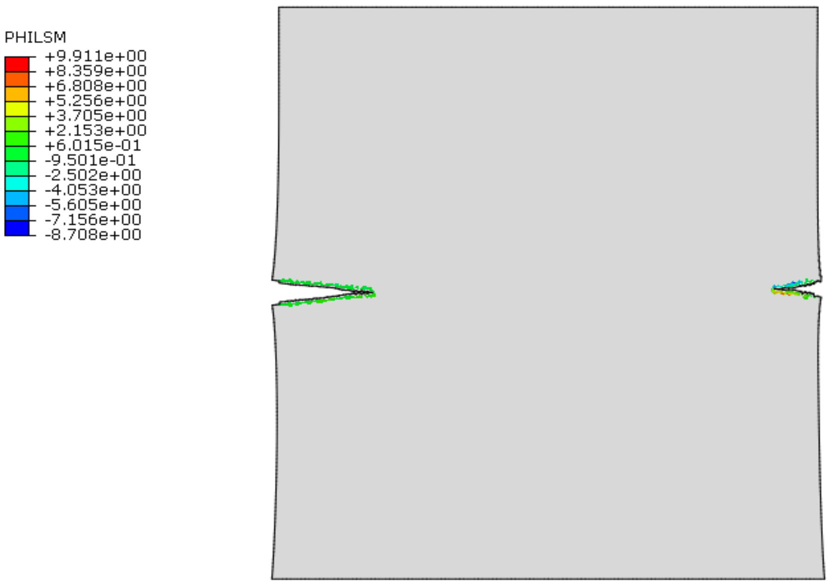


Figure 4.11 Signed distance function plot of RAC with rectangular notch under tension by XFEM using cohesive segment approach

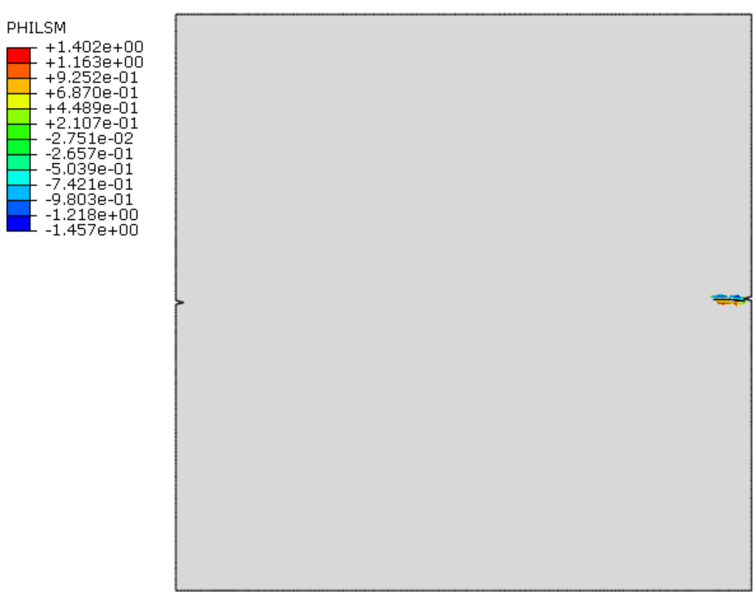


Figure 4.12 Signed distance function plot of RAC with tri-notch under tension by XFEM using cohesive segment approach

4.2.2 Results by XFEM using cohesive segments approach under tension-shear

The PHILSM results given by XFEM using cohesive segments approach under tensile-shear load are presented in Figures 4.13 and 4.14. As expected, the damage of RAC is formed in two inclined cracks which are approximately parallel to each other, which is also reflected in the stress contour in Figure 4.8. The results given in here is closely analogue to the results published in the current literature (Roth et al. 2013)

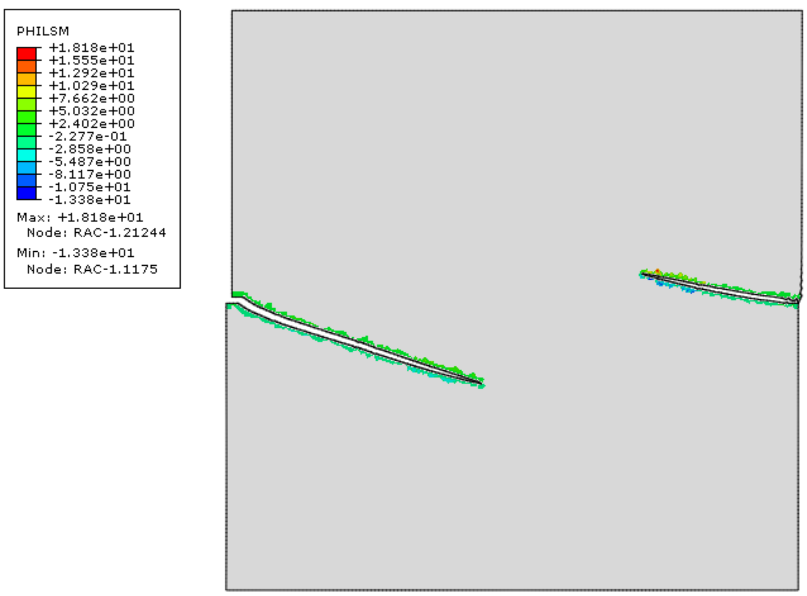


Figure 4.13 Signed distance function plot of RAC under tension-shear by XFEM using cohesive segment approach

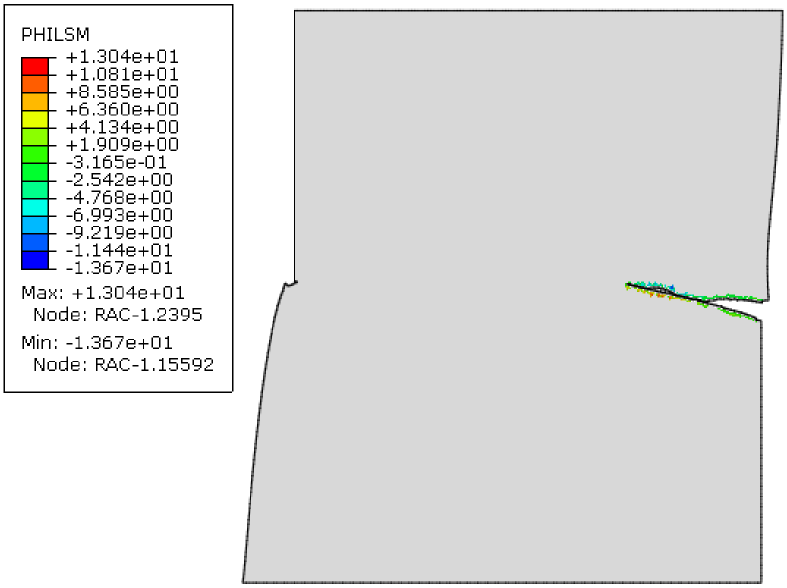


Figure 4.14 Signed distance function plot of RAC with rectangular notches under tension-shear by XFEM using cohesive segment approach

4.2.3 Results by XFEM using LEFM-VCCT under tension and tension-shear

The PHILSM results given by XFEM using LEFM-VCCT approach under tensile-shear load are presented in Figures 4.15 and 4.16. Under either tensile or tensile-shear loads, crack is barely observed. The reason may be due to the nature of linear elastic fracture mechanics, which is not appropriate for the non-brittle materials such as concrete.

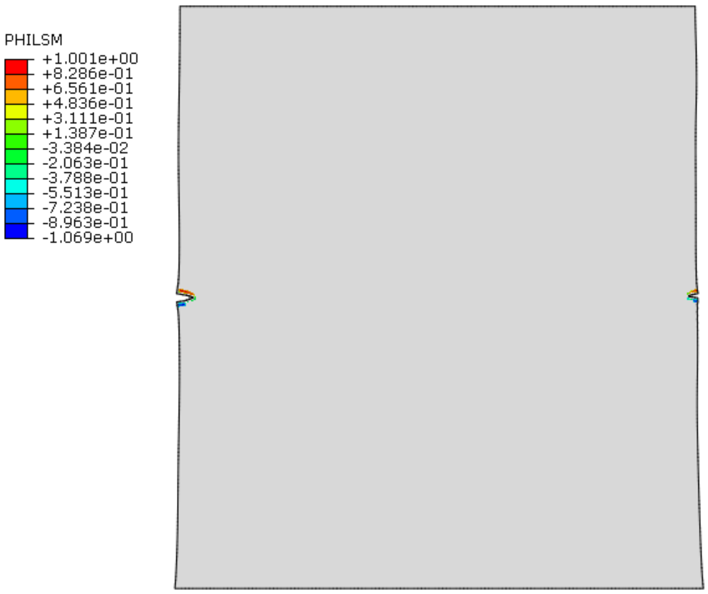


Figure 4.15 Signed distance function plot of RAC under tension by XFEM using LEFM-VCCT approach

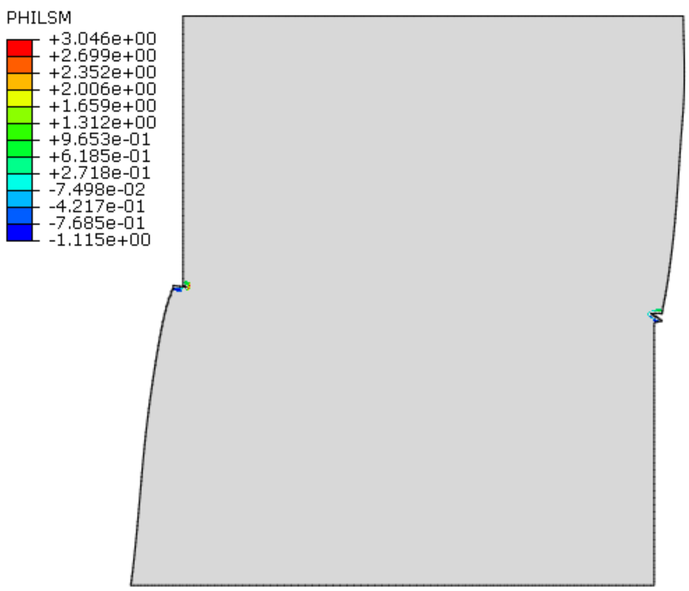


Figure 4.16 Signed distance function plot of RAC under tension-shear by XFEM using LEFM-VCCT approach

CHAPTER 5

CONCLUSION DISCUSSIONS AND FUTURE WORK

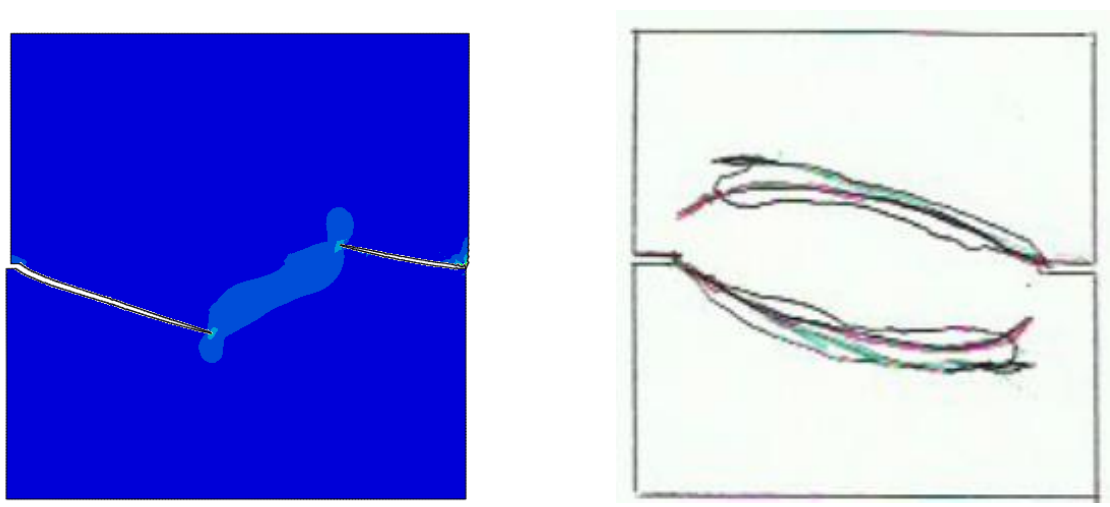
5.1 Conclusion and discussions

Prediction of crack initiation and propagation in both regular and recycled aggregate concrete remains a challenge for researchers. In this work, well established concrete damage plasticity constitutive material model and extended finite element model technique were used to study the crack of both regular and recycled aggregate concretes. The findings are summarized as the followings:

1) Concrete damage plasticity is appealing for obtaining information about critical potential crack regions in concrete. Stationary crack may be clearly displayed by plotting contours of damage parameters.
2) It can be observed that the cracks are generally initiated from regions of ITZs by looking into the results provide by modeling using CDP.
3) Thus RAC may not be as sensitive to crack as regular concrete and crack resistance is improved by using RAC.
4) In terms of stress-strain response, at the linear elastic stage, both RAC and reference regular concrete behave almost the same, but in the softening stage, RAC is expected to experience larger failure strain. RAC may possess higher ductility compared to regular concrete.
5) XFEM is suitable for the modeling of damage initiation and propagation in both recycled

aggregate and regular concrete.

6) The cohesive segment approach of XFEM which is by defining the stress- or strain- based damage initiation criteria, and traction-separation laws as damage evolution criteria, is favorable for detecting crack of RAC. The results given by XFEM cohesive segment approach are comparable to those ones in existing literature (Figure 5.1).
7) Nevertheless, LEFM modeling approach of XFEM may not be an ideal candidate for the modeling of crack in RAC, which may be attributed to the fact that the nature of LEFM is for brittle material whilst concrete is a semi-brittle material.



a. Crack pattern given in this study   b. Crack pattern given by Roth et al. (2013)

Figure 5.1 Comparisons of Crack Patterns

Figure 5.1 (a) shows crack pattern of RAC subjected to tension-shear load by applying XFEM-cohesive segment approach. The crack pattern in Figure 5.1 (a) is closely analogue to the results given by Roth et al. (2013) which is shown in Figure 5.1(b). Both simulations are under similar boundary conditions.

During the simulation procedure, fracture is moderately difficult to converge to a solution, because it is a nonlinear and non-smooth structure response. In order to conquer this difficulty and further improve the convergence, the default time increment parameters are modified to allow discontinuous analysis and also increase the number of attempts permitted for each increment. (Wu, 2015)

5.2 Future work

Concrete damage plasticity material model and extended finite element modeling technique were successfully used to capture the crack patterns, crack initiation and propagation in recycled aggregate concrete. In the current work, the effect of thickness of ITZs on the crack pattern in RAC was not been investigated. Also material properties in different phase materials are fixed. Effect of variation of material properties on concrete damage pattern may have impact on the formation process of crack. Smeared crack concrete damage model might also be employed to study the crack pattern in RAC.

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